REPORT DOCUMENTATION PAGE

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15-12-2015	Final Report	1-Oct-2008 - 30-Sep-2015

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Final Report: Optically Driven Spin Based Quantum Dots for Quantum Computing-Research Area 6 Physics 6.3.2

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6. AUTHORS
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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Ann Arbor, MI 48109 -1274

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14. ABSTRACT
This program conducted experimental and theoretical research aimed at developing an optically driven quantum dot quantum computer, where, the qubit is the spin of the electron trapped in a self-assembled quantum dot in InAs. Optical manipulation using the trion state (2 electrons and a hole) allows for fast (psec) rotations of the electron spin. The program achieved several milestones summarized in the annual reports. In this reporting period, we discovered the nuclear spin quieting first discovered in 2008 is present in vertically coupled quantum dots but

15. SUBJECT TERMS
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Report Title

Final Report: Optically Driven Spin Based Quantum Dots for Quantum Computing-Research Area 6 Physics 6.3.2

ABSTRACT

This program conducted experimental and theoretical research aimed at developing an optically driven quantum dot quantum computer, where, the qubit is the spin of the electron trapped in a self-assembled quantum dot in InAs. Optical manipulation using the trion state (2 electrons and a hole) allows for fast (psec) rotations of the electron spin. The program achieved several milestones summarized in the annual reports. In this reporting period, we discovered the nuclear spin quieting first discovered in 2008 is present in vertically coupled quantum dots but includes an unexpected role of nonlocal nuclear spin quieting. The final reporting period shows the first measured narrowing of the hyperfine field distribution resulting from the nuclear spin quieting. Considerable insight into the physical origin of the nuclear quieting was made in theory that also expanded our understanding of the physics of coupled quantum dots and ways to incorporate this system into a quantum network.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
07/21/2014	18.00	J. Schaibley, A. Burgers, G. McCracken, D. Steel, A. Bracker, D. Gammon, L. Sham. Direct detection of time-resolved Rabi oscillations in a single quantum dot via resonance fluorescence, Physical Review B, (03 2013): 1153111. doi: 10.1103/PhysRevB.87.115311
07/21/2014	16.00	L.?A. Webster, K. Truex, L.-M. Duan, D.?G. Steel, A.?S. Bracker, D. Gammon, L.?J. Sham. Coherent Control to Prepare an InAs Quantum Dot for Spin-Photon Entanglement, Physical Review Letters, (03 2014): 0. doi: 10.1103/PhysRevLett.112.126801
07/21/2014	17.00	Katherine Truex, L. A. Webster, L.-M. Duan, L. J. Sham, D. G. Steel. Coherent control with optical pulses for deterministic spin-photon entanglement, Physical Review B, (11 2013): 1953061. doi: 10.1103/PhysRevB.88.195306
07/25/2014	19.00	Wen Yang, L. Sham. General theory of feedback control of a nuclear spin ensemble in quantum dots, Physical Review B, (12 2013): 235304. doi: 10.1103/PhysRevB.88.235304
07/25/2014	20.00	Guy Z. Cohen, L. J. Sham. Rapid creation of distant entanglement by multiphoton resonant fluorescence, Physical Review B, (12 2013): 2453061. doi: 10.1103/PhysRevB.88.245306
08/15/2013	13.00	J. R. Schaibley, A. P. Burgers, G. A. McCracken, L.-M. Duan, P. R. Berman, D. G. Steel, A. S. Bracker, D. Gammon, L. J. Sham. Demonstration of Quantum Entanglement between a Single Electron Spin Confined to an InAs Quantum Dot and a Photon, Physical Review Letters, (04 2013): 167401. doi: 10.1103/PhysRevLett.110.167401
08/22/2012	11.00	Allan Bracker, Daniel Gammon, L. Sham, Bo Sun, Colin Chow, Duncan Steel. Persistent Narrowing of Nuclear-Spin Fluctuations in InAs Quantum Dots Using Laser Excitation, Physical Review Letters, (5 2012): 0. doi: 10.1103/PhysRevLett.108.187401
08/22/2012	12.00	Bo Sun, Wang Yao, Xiaodong Xu, Allan S. Bracker, Daniel Gammon, L. J. Sham, and Duncan Steel. Persistent Opticl Nuclear Spin Narrowing in a Singly Charged InAs Quantum Dot, Journal of Optical Society of America, (02 2012): 119. doi:
08/22/2012	10.00	Wen Yang, L. Sham. Collective nuclear stabilization in single quantum dots by noncollinear hyperfine interaction, Physical Review B, (06 2012): 0. doi: 10.1103/PhysRevB.85.235319
09/02/2011	5.00	Jing Wang, Ren-Bao Liu, Bang-Fen Zhu, L. Sham, D. Steel. Coherent spin control by electromagnetic vacuum fluctuations, Physical Review A, (5 2011): 0. doi: 10.1103/PhysRevA.83.053833
09/02/2011	2.00	Erik D. Kim, Katherine Truex, Yanwen Wu, A. Amo, Xiaodong Xu, D. G. Steel, A. S. Bracker, D. Gammon, L. J. Sham. Picosecond optical spectroscopy of a single negatively charged self-assembled InAs quantum dot, Applied Physics Letters, (09 2010): 0. doi: 10.1063/1.3487783
09/02/2011	4.00	Ren-Bao Liu, Wang Yao, L.J. Sham. Quantum computing by optical control of electron spins, Advances in Physics, (09 2010): 0. doi: 10.1080/00018732.2010.505452
09/02/2011	6.00	Qiong Huang, Duncan Steel. Optical excitation effects on spin-noise spectroscopy in semiconductors, Physical Review B, (4 2011): 0. doi: 10.1103/PhysRevB.83.155204

Received		Paper
09/02/2011	7.00	A. S. Bracker, D. Gammon, L. J. Sham, D. G. Steel, Erik D. Kim, Katherine Truex, Xiaodong Xu, Bo Sun. Fast Spin Rotations by Optically Controlled Geometric Phases in a Charge-Tunable InAs Quantum Dot, Physical Review Letters, (04 2010): 0. doi: 10.1103/PhysRevLett.104.167401
09/06/2011	9.00	. A Spin Phase Gate Basedon Optically Generated Geometric Phases in a Self-Assembled Quantum Dot, , (06 2011): 0. doi:

TOTAL: **15**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

A. Burgers, D.G. Steel, "Coherent Optical Control of Quantum Dots: Spin Qubits and Flying Qubits", APS March Meeting, San Antonio, TX, 2015.

Colin M. Chow, Aaron M. Ross, L. J. Sham, Allan S. Bracker, Dan Gammon, Duncan G. Steel "Coherent Optical Control of the Electron and Nuclear Spin in a Quantum Dot Molecule ", Frontiers in Optical Physics in Semiconductors, Breckinridge, Colorado (2015)

Colin M. Chow, Aaron M. Ross, Daniel Gammon, Allan S. Bracker, L. J. Sham, Duncan G. Steel, "Optical Spin State Preparation of Two Electrons Confined in an InAs Quantum Dot Molecule," CLEO/QELS San Jose (2015).

Aaron M. Ross, Colin M. Chow, Daniel Gammon, Allan S. Bracker, L. J. Sham, Duncan G. Steel, "Nuclear Spin Narrowing in an InAs Quantum Dot Molecule: Extension of Two-Electron Spin Decoherence Time," CLEO/QELS, San Jose (2015.

Colin M. Chow, Aaron M. Ross, Lu J. Sham, Allan S. Bracker, Daniel Gammon, Duncan G. Steel, "Nuclear Spin Locking and Extended Two-Electron Spin Decoherence Time in an InAs Quantum Dot Molecule," APS March Meeting, San Antonio (2015).

Aaron M. Ross, Colin M. Chow, L. J. Sham, Allan S. Bracker, Daniel Gammon, Duncan G. Steel, "Ground state initialization in a doubly-charged, vertically-stacked InAs quantum dot molecule,' APS March Meeting, San Antonio (2015).

Number of Presentations: 6.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper	
09/02/2011	3.00	Erik D. Kim, Katherine Truex, Xiaodong Xu, Bo Sun, D. G. Steel, Allan S. Bracker, Daniel Gammon, Lu Sham. Fast optically driven spin qubit gates in an InAs quantum dot, Advances in Photonics of Quantum Computing, Memory, and Communication III. 28-JAN-10, San Francisco, California, USA. : ,
TOTAL:	**1**	

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper
TOTAL:	

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
08/15/2013	14.00	Wen Yang, L. J. Sham. General theory of feedback control of a nuclear spin ensemble in quantum dots, ArXiv e-prints (07 2013)
09/02/2011	1.00	Wen Yang, L. J. Sham. Collective Nuclear Stabilization by Optically Excited Hole in Quantum Dot, (01 2011)
09/06/2011	8.00	. Persistent Optical Nuclear Spin Narrowing, (04 2011)
12/14/2015	23.00	Guy Coherent. Complete All-Optical Quantum Control of Electron Spins in InAs/GaAs QuantumDot Molecule, arXiv:1501.00342.0195v1 (01 2015)
12/15/2015	24.00	Colin Chou, Aaron Ross, Danny Kim, Daniel Gammon, Allan Bracker, LJ Sham, DG Steel. Non-local nuclear spin quieting in quantum dot molecules:Optically-induced extended two-electron spin coherence time, PHYSICAL REVIEW Letters (Submitted) (12 2015)

TOTAL: **5**

Number of Manuscripts:

Books

Received Book

TOTAL:

Received	Book Chapter
12/14/2015 21.00	Duncan Steel. Laser Spedtroscopy and Quantum Optics in GaAs and InAs Semiconductor Quantum Dots, United Kingdom: Elseveir, (09 2015)
12/15/2015 22.00	Alex Burgers, John Schaibley, Duncan Steel. Entanglement and Quantum Optics with Quantum Dots, New Jersey: World Scientific Reviews , (08 2015)

TOTAL: **2**

Patents Submitted

Patents Awarded

Awards

none during this period

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Colin Chou	0.50	
Akex Burgers	0.50	
Aaron Ross	0.50	
Uttam Paudel	0.50	
FTE Equivalent:	**2.00**	
Total Number:	**4**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Guy Cohen	0.50
FTE Equivalent:	**0.50**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
LJ Sham	0.00	Yes
DG Steel	0.00	No
FTE Equivalent:	**0.00**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Humza Khan	0.20	Electrical Engineering
FTE Equivalent:	**0.20**	
Total Number:	**1**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME	
n/a	
Total Number:	**1**

Names of personnel receiving PHDs

NAME	
Alex Burgers	
Colin Chou	
Total Number:	**2**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

see attachment

Technology Transfer

We have interacted with our collaborators Dan Gammon and Allan Bracker at NRL.

FINAL REPORT

Optically Driven Spin Based Quantum Dots for Quantum Computing

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ARO PROPOSAL NUMBER: 55014-PH-QC
FUNDING PERIOD: 10/01/08-9/30/15
GRANT NUMBER: W911NF-08-1-0487

ABSTRACT

NOTE: Following Form B, Item 2B1, data reported for period of Aug 1, 2014 – Sept. 30, 2015

This program conducted experimental and theoretical research aimed at developing an optically driven quantum dot quantum computer, where, the qubit is the spin of the electron trapped in a self-assembled quantum dot in InAs. Optical manipulation using the trion state (2 electrons and a hole) allows for fast (psec) rotations of the electron spin. The program achieved several milestones summarized in the annual reports. In this reporting period, we discovered the nuclear spin quieting first discovered in 2008 is present in vertically coupled quantum dots but includes an unexpected role of nonlocal nuclear spin quieting. The final reporting period shows the first measured narrowing of the hyperfine field distribution resulting from the nuclear spin quieting. Considerable insight into the physical origin of the nuclear quieting was made in theory that also expanded our understanding of the physics of coupled quantum dots and ways to incorporate this system into a quantum network.

Introduction

This work focused on the study and development of single electron doped semiconductor quantum dots (QD) for application to the problem of optically driven quantum computing and future spin based quantum devices. The developments in this field are based on the recent advances in fabrication and nano-optical-probing and the new developments of our own group that have contributed with the first measurements and theory in coherent nonlinear optical manipulation of these systems. The primary advantage of the optical approach is that it allows for device speeds to be in the 100 GHz region, as discussed and demonstrated earlier with ARO support, orders of magnitude faster than many competing approaches for quantum architectures. Also, the absence of wires for electrical pulses reduces the architectural complexity as dimensions become smaller which would also lead to higher electrode densities.

Objective

This work focuses on the study and development of doped semiconductor quantum dots (QD) for application to the problem of optically driven quantum computing. The developments in this field are based on the recent advances in fabrication and nano-optical-probing that have contributed with the first measurements and theory in coherent nonlinear optical manipulation of these systems.

Approach

Our approach to the study of these systems is based on the use of coherent nonlinear laser spectroscopy, coherent transient excitation and optical control, and the use of advanced materials. The qubit of interest is the electron spin confined to a semiconductor quantum dot. Coherent control of the system is achieved by coherent optical excitation. Materials are grown by MBE and further processing by lithography techniques by Dan Gammon and his group at NRL. This group also uses advanced spectroscopy methods to develop and demonstrate the physics of these structures.

The dots are self-assembled quantum dots (SAQD) in Schottky diodes. Based on spins in these dots, a scalable architecture has been proposed [Adv. in Physics, 59, 703 (2010)] by us based on the possibility of single spin rotation and some logic gates between two qubits either in neighboring dots or in distant locations. The qubit can experience an arbitrary rotation by excitation through a virtually excited trion state using a coherent Raman type excitation. Entanglement between spins in adjacent dots is accomplished by a modified optical RKKY (ORKKY) interaction yielding a Heisenberg Hamiltonian coupling between the two spins or Coulomb coupling between the trion states [Phys. Rev. Lett. **89**, 167402 (2002)]. High speed state initialization is achieved by spin cooling techniques. Figure 1a and 1b show the basic idea of a quantum dot spin qubit based on InAs/GaAs SAQDs shown in the many-particle picture for linear polarization selection rules. Figure 1a is the energy level structure for a single dot with one additional electron and Fig. 1b is the energy level structure for a coupled quantum dot system (a quantum dot molecule) with one extra electron in each dot and coupled by the exchange interaction in the ground state. By adding a single electron to a quantum dot, the ground state becomes doubly degenerate spin state and is known to exhibit long relaxation times. The long relaxation time is expected to lead to long coherence times. A scalable system is

achieved by creating an array of dots within a few 10's of nanometers of each other or clusters of smaller numbers connected by flying qubits. With the discovery of spin fluctuation freezing on this program [*Nature* **459**, pp1105-1109 (2009)], quantum dot spins have a more than adequate spin coherence time to enable error correction.

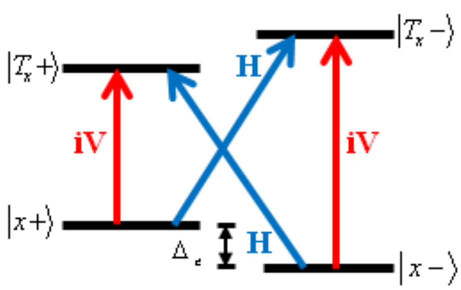

Figure 1a. Energy level diagram for a negatively charged QD in a magnetic field in the Voigt geometry with linearly polarized light along the red and blue transitions.

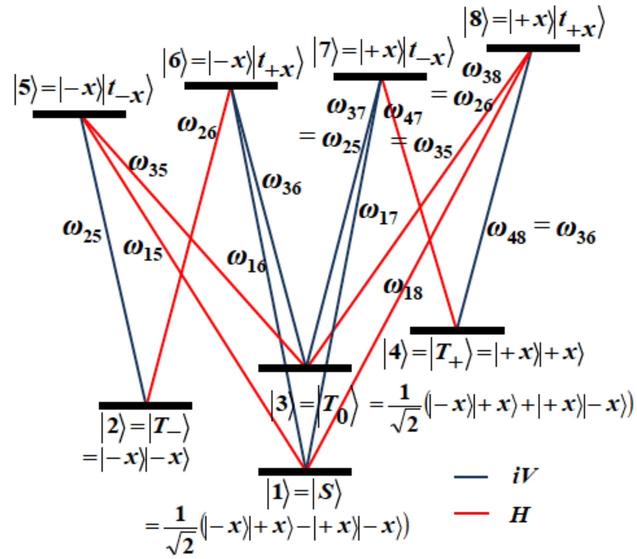

Figure 1b. Energy level diagram for a quantum dot molecule showing dipole-allowed optical transitions between singlet/triplet ground states and optically excited states in the presence of an in-plane (Voigt geometry) magnetic field. States consist of an electron in the lower QD, represented by $|\pm x\rangle$, and a trion in the upper QD, represented by $|t_{\pm x}\rangle$. Here, spin projections are shown along +x-direction and +(-) denotes spin up (down). Blue (red) lines represent vertical (horizontal) polarization.

Scientific Progress

Development of a 2-qubit gate using quantum dot molecules (QDM) and the control of nuclear spin fluctuations

We reported during the previous funding period our progress demonstrating initialization of the four states in the singlet-triplet manifold and our ability to lock the nuclear spins and increase the electron-spin coherence time by at least a factor of 500 through nonlocal coupling. During this final research period, we performed additional spectroscopy measurements that has allowed us to make the first direct measurement of the impact of the optical fields on the Overhauser field distribution. Using the various pump and probe arrangements in Fig. 2a and the resultant spectral line shapes recorded in Fig. 2b, we carry out simulations of the modified optical Bloch equations of the type we developed years ago with ARO support to extract the corresponding Overhauser field distributions shown in Fig. 2c. The corresponding lineshapes that are predicted are shown in Fig. 2d. Most dramatic is the presence of the coherent dark state dip in Fig. 2b in the presence of pump 3, and the absence of pump 3, contrary to the theory of the dark state

resonance, no dark state dip is observed. Moreover, in both cases the overall lineshape deviates from the coherent population trapping theory. This is a direct result of the role of pump 3 in stabilizing the fluctuations in the Overhauser distribution and narrowing the average distribution. Fig. 2c shows the distribution obtained by fitting the theoretical lineshape predicted by the modified optical Bloch equations. The clear narrowing of the distribution is seen in Fig. 2c along with an excellent fit to the data in the presence of the third pump field. The effect of pump of 3 is to use the coherent superposition created by the strong pumps between the singlet and the T_+ state to stabilize the Overhauser field fluctuations and extend the coherence time o the electron spins to enable observation of the dark state dip between the S-T_- and the S-T_+ systems, respectively. A manuscript has been prepared and submitted to PRL.

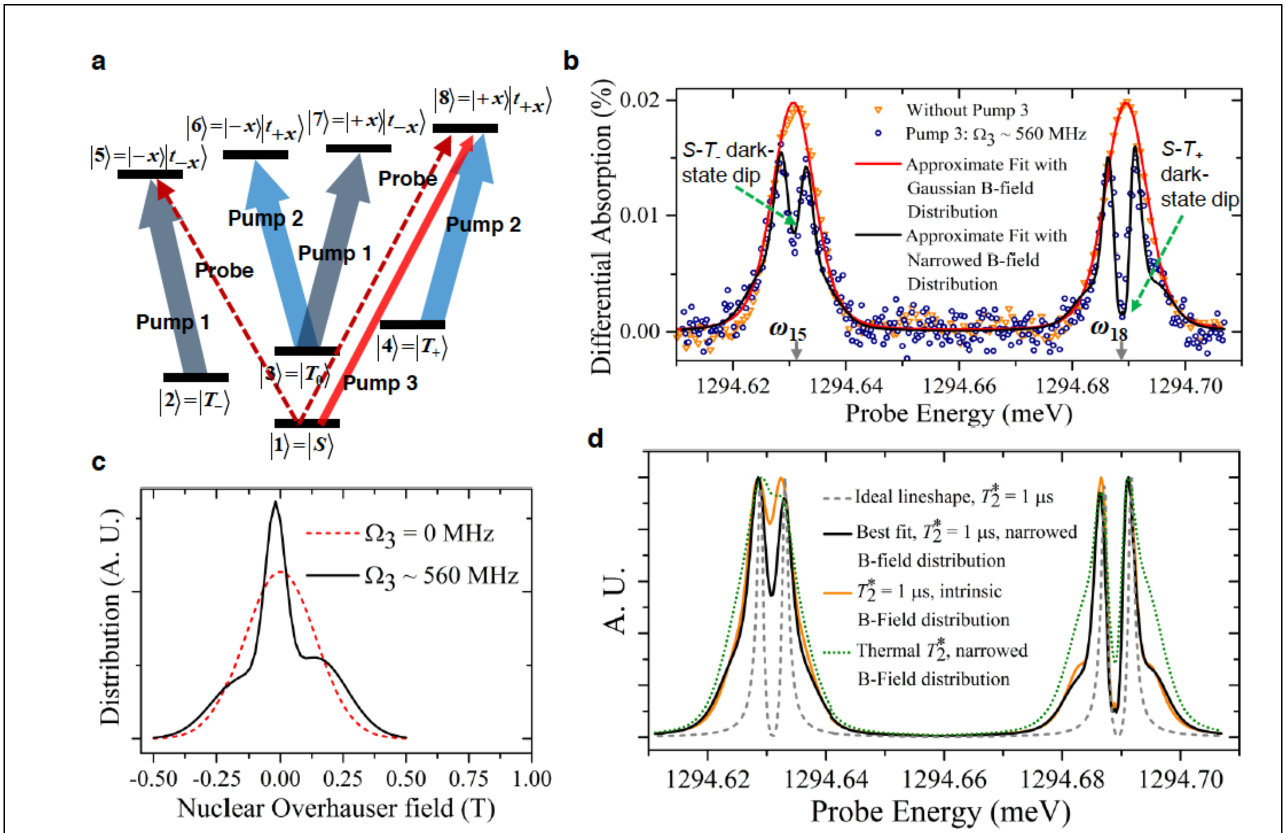

FIG. 2. Suppression of DNSP by optical nuclear spin locking. a. Pump configuration for $\mathbf{T}_+$ state preparation. b. Probe absorption spectra following the pumping scheme in a. In the upper panel, the vertically polarized probe is scanned in forward direction across $\omega_{48/36}$ transition. In the lower panel, the probe laser is scanned in backward direction. The spectra show hysteresis due to DNSP with the QD resonance seeming to move away from the approaching probe frequency. c. Pump 3 is added to the configuration shown in a to suppress the effect of DNSP. d. Probe absorption spectrum showing the recovery of dark-state profile. Solid circles in the plot represent averaged data points obtained from a series of 7 scans and the error bars show standard deviations. Red solid lines is the theoretical fit.

The coupled quantum dots as a network node

The isolate two electron qubits housed in two coupled quantum dots with tunneling between them, as described above, may not be scalable but can serve as a node in a quantum network. The new aspect of the theory in this research period is the investigation of the optical control of

the minimal set of quantum gates of the tunneling-coupled two-electron spin ground states in the vertically coupled quantum dots for "universal computation" two spin qubits within the universe of the spin states and the four optically excited auxiliary states. The preprint (http://arxiv.org/abs/1501.01952v1) represents some preliminary work on schemes for making a minimal set of gates by optical control and applying pulse-shaping methods developed previously by Sham's group to increase the efficiency of the gates.

Progress on creating a quantum entanglement between two quantum dot spins separated by a distance

A key component in the teleportation experiment is demonstrating interference between two photons: the photon carrying the information to be teleported and the photon entangled with the target qubit (electron spin). Two-photon interference is demonstrated in a HOM- (Hong-Ou-Mandel-) interferometer. To advance our work on the teleportation, we demonstrated a functioning HOM by demonstrating two-photon interference between sequentially emitted photons from a single quantum dot. The basic experimental idea is shown in Fig. 3a. The dot is illuminated with a cw laser and resonant Rayleigh scattered light is collected and sent to the first beam splitter. Since the two photons are emitted at different times, there is 50% probability that they will take different paths after the beam splitter. If the photons are not identical (by polarization, time, etc.), then they will not interfere on the HOM beam splitter (BS2) and hence take different paths giving a coincidence pulse for some finite time separation. However, if the photons are identical and overlap in time, they will interfere constructively and both will take one path or the other, resulting in no coincidence. Hence, the coincidence rate falls to zero in the ideal case for a zero coincidence time. The experimental data in Fig. 3b shows a strong dip in the coincidence rate for the time difference at t=0. A second dip on each side of t=0 is due to a weaker interference coming from photons emitter earlier corresponding to the fixed path length difference between the two arms. The oscillations in the data not included in the theory arise from a weak Rabi oscillation.

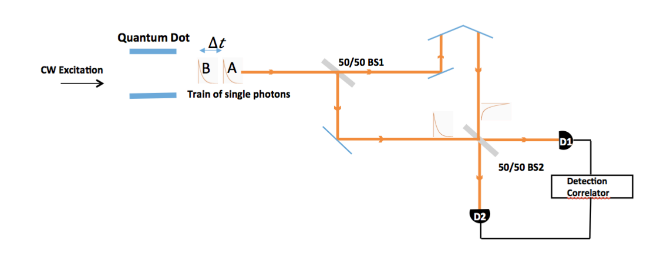

Figure 3a. Experimental configuration for demonstrating two-photon interference from sequentially emitted photons from a single quantum dot. The second beam splitter forms the HOM interferometer for identifying indistinguishable photons.

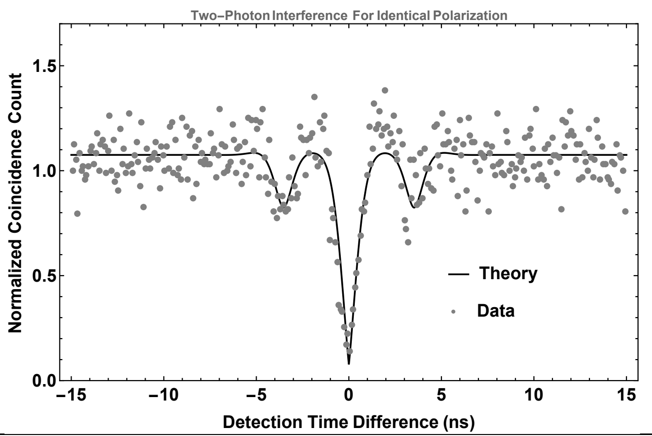

Figure 3b. Data showing two photon interference from sequentially emitted photons. The x-axis represents the time difference recorded by the coincidence detector. When two photons interfere constructively on the second beam splitter, no coindidence is detected. A deep minimum occurs at t=0 showing a high degree similarity between the two photons. The secondary resonances shows a drop in coincidence at the time corressponding to the path length difference in the interferometer.